Multivideo Source Image Processing for Beam Profile Monitoring System*

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Abstract. Some experiments at Jefferson Lab demand tight beam size ($\approx$100 μm) and very low energy spread (< 5 10^{-5}). These experiments also require simultaneous and continuous monitoring of these quantities. This paper focuses on the development of the image processing aspects of the beam profile monitoring system. A pipelined image processor, Datacube's MaxVideo MV200, calculates beam sizes and positions from two beam profile monitors simultaneously at 10 Hz rate. Multiplexing software in the EPICS environment allows a single digitizer to process several input channels at high speed. This system makes the profile monitors usable for tuning the accelerator, as well as delivering critical information to the end stations. This paper discusses the issues related to the daily operational use of the system. The availability and reliability of the monitoring system became acceptable only after the implementation of programs that automatically setup and periodically check the monitors and digitizer. The system permits additional video channels without significant additional hardware cost.

INTRODUCTION

By means of two superconducting linacs, with beam recirculated up to five times, CEBAF provides nuclear physics experiments with high power (up to 0.8 MW) electron beams of high quality. Standard beam energies range from 0.8 to 5.5 GeV. The beam intensity ranges for the three end stations are: 1 to 180 μA for Hall A, 1 to 30 nA for Hall B, and 0.1 to 180 μA for Hall C. A growing number of experiments in the three end-stations have begun to require small transverse beam size (present: 100 μm < $\sigma_{x \text{ and } y}$< 200 μm; future: 20 μm < $\sigma_{x \text{ and } y}$< 200 μm) and low energy spread (present: dE/E < 5 E-5; future: dE/E < 2.5 E-5). Continuous monitoring of the beam profile at critical points of the accelerator and experimental lines is becoming necessary. This monitoring is also helpful in tuning the machine's optics.

Optical Transition Radiation (OTR) monitors at the 4 m dispersion point of the high current experimental lines (Halls A and C) provide continuous energy spread data at a 5 Hz repetition rate. An image digitizer connected to the monitors computes beam size and position, using the forward OTR. This paper focuses on the hardware and software implementations that convert the beam profile video signals into positions and RMS beam sizes, which then become part of the experiment's data.

The high cost of digitizers (~30 K$) makes equipping each video monitor with its own unit impractical. Until recently, the accelerator and end stations periodically (not

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continuously) measured beam profiles and positions at a single monitor location. One MV200 (Fig. 1b) with dedicated software [4] running under the EPICS control system accomplished this task [6]. The requirement of continuous energy spread monitoring at several locations, (at high rate), prompted using the digitizer's capability of multiplexing up to four video signal inputs into its image processing unit. This multiplexing feature required the development of specialized software. The pay back is reduced hardware cost.

Several problems involving the operator interface appeared during the system commissioning. Setting up the digitizer manually was a task only a few experts could perform, which took at least 15 minutes per monitor. An initialization script obviated the expert intervention and reduced the initialization setup to about 5 minutes. Another script periodically checked the setup parameters and camera pixel illumination, readjusting them as needed.

ENERGY SPREAD AND OTHER CEBAF PROFILE MONITORS

Initially, the accelerator had a large number of insertable Chromox-6 fluorescent screens for routine tuning of the machine. The fast update rate of the image is convenient. However, the screens are invasive, can only withstand low current (1 μA average) and have poor resolution (~ 0.5mm, compared to standard accelerator beam sizes of < 100 μm). In addition, due to their invasive nature, simultaneous measurements with multiple screens are not possible. They are still useful for quantitative measurements of the energy spread at high dispersion locations in the injector where the beam is several millimeters wide, and near the septa where the beam position monitors cannot measure several beams having different positions.

The accelerator also has wire scanners, which can provide high-resolution profile measurements. However, any manual tune-up of the optics using the wire scanners is time consuming because their speed does not exceed one scan per minute. In addition, the wire scanners cannot withstand the maximum beam current, are invasive and are not useful for continuous monitoring during beam delivery. The three types of profile monitors, either developed or under development at Jefferson Lab, are:

- OTR monitors at 4 m dispersion points in experimental lines A and C. Using a 0.25 μm thick carbon foil, these monitors, (described in references [1] and [2]), can tolerate the maximum beam current. Their resolution, though limited by the camera (2 pixels ≈ 60 um), is adequate. The thinness of the foil allows continuous monitoring of the beam with little impact on the experiment due to beam scattering. However, in a few instances of simultaneous low energy and high current beams, the amount of radiation along one of the experimental lines was too high to leave the foil in the beam path. In these few cases, periodic monitoring was the only acceptable solution. Moving the OTR foil near to the target will solve this problem.
- New high resolution fluorescent screens [3] using YAG:Ce (Cerium doped Yttrium Aluminum Garnet): In the low current (down to 1 nA) experimental line B, the OTR does not produce sufficient light. Replacing the present chromox-6 material with 0.1 mm thick YAG:Ce will provide the required 50 um RMS beam

size resolution at relatively low cost and cover the dynamic range of beam currents needed in that particular beam line. This is an invasive technique.

- Synchrotron Light Monitors (SLM). Presently in use in the first two arcs of the accelerator, these devices are good down to a few nA of beam current. In the experimental lines, with a bending radius of 30 to 40 m, the limit to their resolution is about 100 μm in the visible spectrum. The resolution is better in the UV spectrum. A mirror mounted in a 3-way cross will direct the synchrotron light to a CCD camera through a horizontal slit, a lens and a set of three neutral density filters (attenuation factors of 0 to 3200). Although the resolution is not as good as that of an OTR, the SLM is viable in high current and low energy regions where beam scattering in the OTR foil can be a problem.

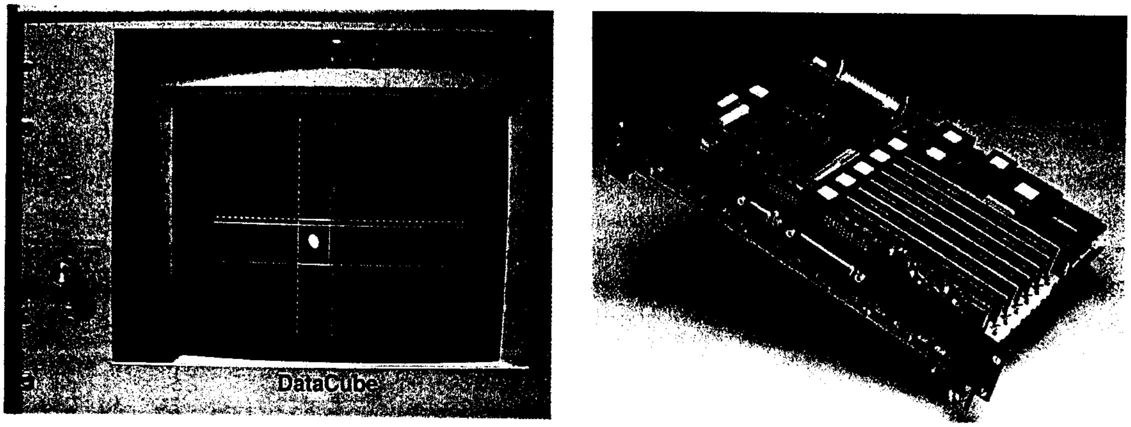
MACHINE OPERATIONS ISSUES

The daily operation of the accelerator requires a broad knowledge of many subsystems such as RF, magnets, cryogenics and beam diagnostics. Effective diagnostics requires automation. The beam profile monitors, based on MV200 programmed with ImageFlow [5] and the EPICS toolkit [6] provide this automation. The MV200 continually processes a large volume of pixels corresponding to 60 Hz interlaced video frames using parallel pipeline technology. This technology allows customization and reconfiguration of any specialized video processing task. EPICS provides users with reliable control mechanisms and excellent graphical user interface. The MV200 and EPICS together make the beam profile monitoring system very powerful.

As seen in Figure 1a, the beam spot occupies a small region on the image frame. Proper processing requires masking the pixels outside the region of interest around the beam. Manually setting up of the mask and loading the required parameters into the MV200 was a lengthy and cumbersome task. Some of the parameters unique to each video source included pixel calibration data, intensity adjustment values for the MV200, and neutral density filter controls. The automated setup procedure implements an auto-masking function which loads the calibration parameters from a file. The routine then masks the beam spot's periphery and adjusts the neutral density filter (if any) in front of the selected camera.

The auto-mask function, developed using the TCL/TK toolkit, uses an iterative process to localize a mask box around the beam spot and to increase the light attenuation until there are no saturated pixels. The program communicates with the MV200 through the EPICS Channel Access protocol and runs from an operator interface (OPI) console. The automatic attenuation and auto-mask routine uses continually updated EPICS database records that contain the number of saturated pixels and the new mask sub-region on the video image. The TCL/TK program masked a region 5 σ in width in X and Y around the beam image and there were no pixels in saturation.

After the completion of the initial auto-mask setup, change in the beam current and position can require new adjustments. To avoid constant operator attention to these



(a) (b)

FIGURE 1. MaxVideo beam monitoring calibration screen (a) and basic MaxVideo 200 board (b).

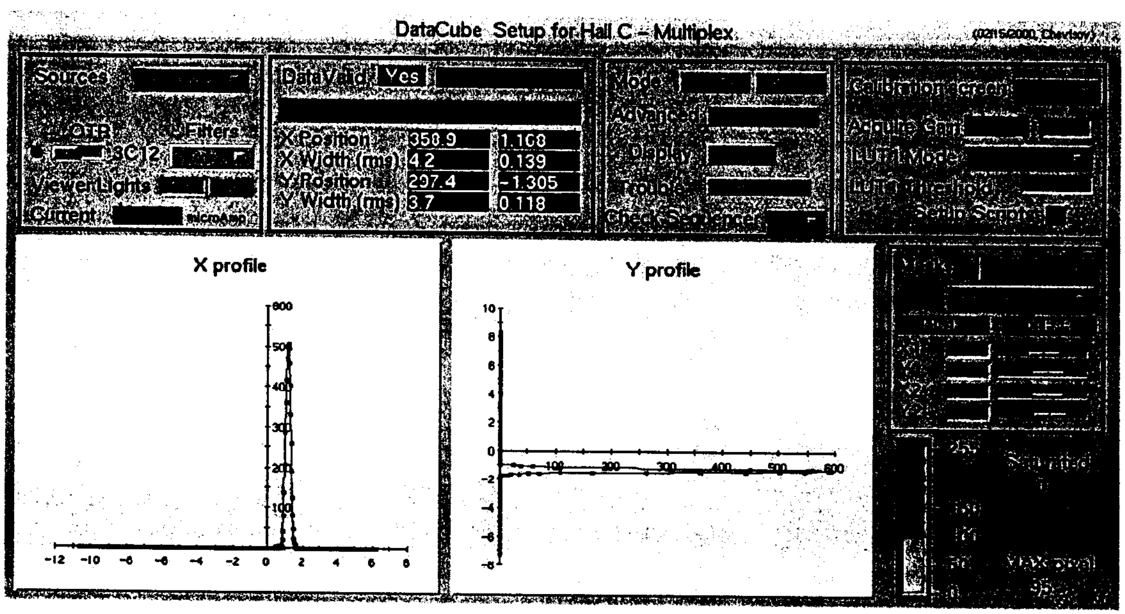


FIGURE 2. Main beam monitoring graphical user interface (MEDM) screen.

changes, an EPICS sequencer program periodically checks pixel illumination and proper beam position inside the mask.

Removal of the burden of manual setups and continuous beam profile observations allowed the MV200 to become a very effective and reliable tool for operations staff.

HARDWARE AND SOFTWARE DEVELOPMENT FOR BEAM PROFILE MONITORING

The most common computers of the accelerator control system at Jefferson Lab are Motorola 680x0 based MVME167 and MVME177 CPUs. EPICS refers to these computers as Input/Output Controllers or IOCs. The latest versions of the MV200 interface software library, ImageFlow, do not support these processors. This necessitated the use of a new hardware configuration, consisting of a basic MV200 board and a Motorola PowerPC based (MVME2700) IOC. The significantly higher performance of the MVME2700 made it very attractive for image processing applications. The PowerPC is a relatively new CPU type for Jefferson Lab and the

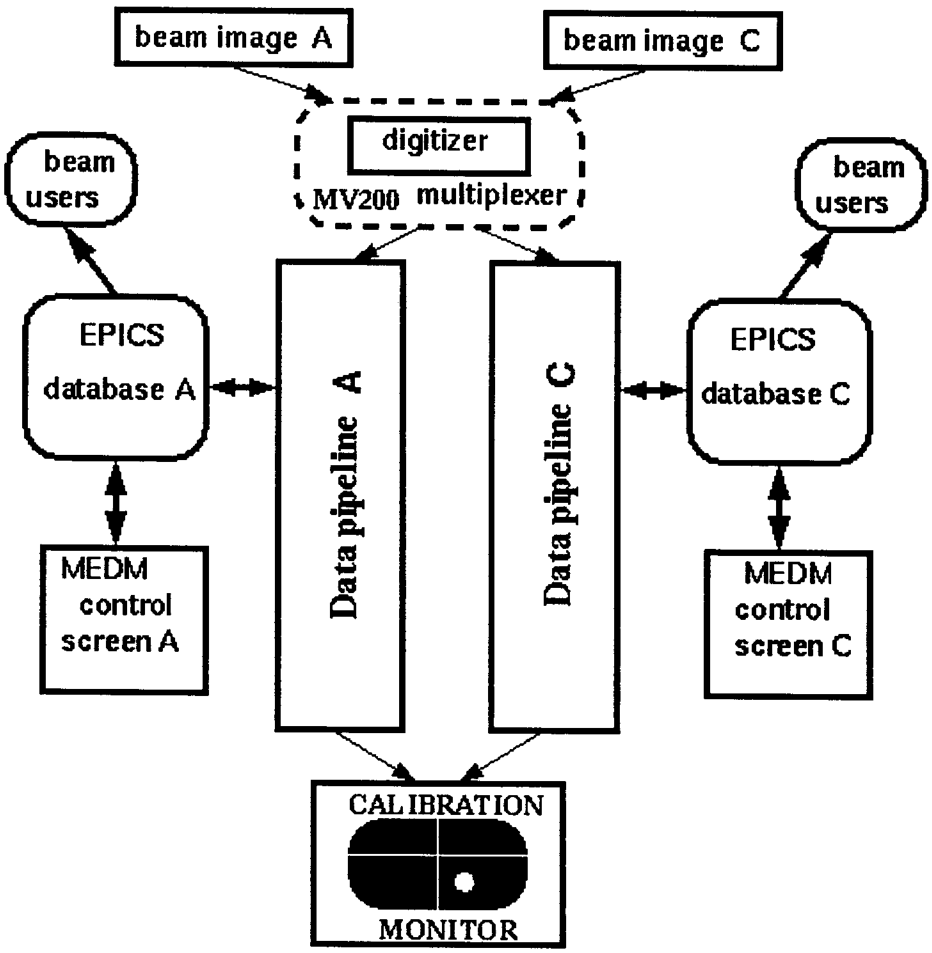


FIGURE 3. Multiplex and multi-pipeline beam profile monitoring system.

experience acquired with it is beneficial for future control system activities at the laboratory. Development of the new multiplex and multi-pipeline beam profile monitoring software used this new hardware configuration.

The MV200 performed all basic calculations. The distributed real-time EPICS database controlled data processing parameters and kept all necessary information pertaining to each video input channel. A single MV200 digitizer digitized images from all video sources. Software control of the MV200's internal video input multiplexer accomplished input channel switching. The design of this multiplex software guarantees uninterrupted and complete processing of each captured data frame. The digital data corresponding to each video source fill their own MV200 data pipeline (Fig. 3), completely separating the data analysis of each video channel. The control parameters for each video source are available from the dedicated main beam monitoring graphical user interface (EPICS MEDM) screen (Fig. 2). This accelerator operator designed screen combines all control functions and is very easy to use. One such screen exists for each video source. From the point of view of a user working with these screens each video source appears to have its own MV200 system.

The RMS beam size and position are calculated at 5 to 10 Hz rate. These calculations use important additional parameters such as the region of interest on a video image (mask) and the calibration data to transform pixels into mm.

A configuration file contains the calibration data corresponding to each video source. As it starts, the multiplexing software reads these data and loads them into the EPICS database. The EPICS sequencer program, mentioned in the previous section, monitors the mask setting and readjusts it as necessary. It also controls the set of optical filters that configure each video monitor in order to avoid pixel saturation. The sequencer keeps the maximum pixel value in a region of good linearity for the video camera. Another sequencer controls a "data valid" flag. The beam users need this flag to discard meaningless MV200 data. Valid data requires that there is enough beam current in the accelerator, the OTR foil is in the beam, proper mask exists, and the maximum pixel value is in the proper range.

CONCLUSIONS

The first months of operation of the new beam profile monitoring system have demonstrated its very high effectiveness. The system has simultaneously provided two different nuclear physics experiments with continuous beam profile monitoring using only one video image processor. It features automated data acquisition and image processing functionality. Use of this multiplexing solution for future beam profile monitoring will make this a very powerful and cost effective system.

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